254

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RESEARCH MEMORANDUM

INVESTIGATION OF CONDITIONS FOR SPONTANEOUS IGNITION AND COMBUSTION EFFICIENCY OF PENTABORANE IN A SMALL-SCALE COMBUSTOR (U)

By Albert M. Lord and James F. Morris

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Cleveland, Ohio

CLASSIFIED DOCUMENT

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

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RESEARCH MEMORANDUM

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3482

CR-1

SUMMARY

A small-scale ram-jet combustor was used to investigate the conditions for spontaneous ignition of pentaborane, amyl nitrate, propylene oxide, and JP-4 fuel. Impulse measurements were made with the pentaborane to give data on combustion efficiency for a combustor with short residence time for mixing and burning.

For the range of conditions investigated, the threshold of spontaneous ignition of pentaborane is governed principally by temperature and is also influenced by burner length and configuration. Spontaneous ignition temperatures of 362° and 474° F for pentaborane were determined for two combustors. The test conditions covered velocities from 280 to 960 feet per second and equivalence ratios from 0.135 to 1.158.

Combustion efficiency increased with increase in burner length and blocked area of the flame holder. There was a decrease in combustion efficiency with increasing equivalence ratio. The combustion efficiency levels were higher for configurations having greater friction pressure loss.

The combustor with the flame holder of 50 percent blocked area experienced continuous increase in friction pressure loss due to solid deposits on the upstream surface of the flame holder.

INTRODUCTION

In cooperation with the Bureau of Aeronautics, Department of the Navy, the NACA Lewis laboratory is investigating the use of boron hydride fuels to extend the range, thrust, and operational limits of jet propelled aircraft. To date experimental and analytical studies have been made with diborane, pentaborane, and several reaction products of diborane and decaborane with several pure hydrocarbons.

The hydride-hydrocarbon reaction products are being prepared in laboratory quantities only; their small supply has limited experimental studies to small-scale exploratory test work on their relative reactivities. Most of the current research is with pentaborane because it is a liquid at room temperature and atmospheric pressure, has a high heating value, and yields exhaust products that are representative of the boron hydride fuels. Pentaborane is relatively available and to date has provided data that demonstrate conditions where it is superior to conventional fuels.

3482

In experimental ram-jet combustors pentaborane has extended operational limits and thrust levels over conventional fuels. Also pentaborane has been evaluated in a turbojet combustor with efficiencies equal to or higher than those realized with JP-4 fuel (ref. 1).

Over and above the high heats of combustion that have been achieved in practical combustor systems, it has been noted that the boron-hydride fuels are exceedingly reactive. Recent experimental studies have demonstrated the large increase in ignitibility and burning velocity of boron-hydride fuels over conventional hydrocarbon fuels. Small concentrations of decaborane substantially reduced the minimum ignition temperature of gasoline (ref. 2). Flame speeds up to nearly 1400 centimeters per second were found for pentaborane-ethane-air mixtures (ref. 3), nearly 16 times the maximum for ethane alone. Liquid pentaborane will ignite with air at room temperature (ref. 4) and diborane in air had flame speeds over 50 times that of hexane (ref. 5).

Reference 6 describes the performance of a turbojet combustor that had been modified to make it suitable for pentaborane fuel. Subsequently, it was found that with this combustor at an air inlet pressure of 1/2 atmosphere, velocity of 105 feet per second, and temperature of 268° F, JP-4 fuel could not be ignited, while pentaborane burned with an efficiency of 98 percent.

A small-scale combustor is described in reference 7 in which the blow-out velocities of a range of pentaborane - JP-4 fuel mixtures were measured. The blow-out velocity of the mixtures increased with increase of pentaborane fraction. It was also shown that in this apparatus the blow-out velocities of conventional fuels varied in the same way as their flame speeds determined by the Bunsen flame method. The apparatus of reference 7 was used to investigate the reactivity of several boron hydride - hydrocarbon reaction products in solution with JP-4. The results (unpublished) indicate that the addition of these hydrides increases the blow-out velocity of JP-4.

The high reactivity of the boron-hydride fuels has suggested their use for extending the range of engine operating conditions where satisfactory combustion efficiency and successful ignition of the combustor

can be achieved. These fuels might also be used in applications where a limited combustion volume makes conventional fuels appear impractical. For example, the high reactivity of pentaborane may make it possible to achieve high combustion efficiencies in small ram jets mounted on the tip of helicopter blades or to shorten turbojet combustors to the point where interstage burners for turbojet engines may be practical.

In this investigation the conditions for spontaneous ignition of pentaborane in a small-volume, high-velocity ram-jet combustor were determined. The combustion efficiency under these relatively unfavorable combustion conditions was also measured. No attempt was made to comprehensively simulate the conditions of operation encountered in the many applications suggested by the special characteristics of the boron hydride fuels. The range of experimental conditions covered had to be severely curtailed by the high cost and limited supply of the fuel. The scope of this investigation was therefore restricted to a $1\frac{7}{8}$-inch diameter combustor which provided low residence periods for mixing and combustion and which was instrumented to record combustion performance with very short burning periods. The project is considered as a "feeler" experiment in which directions for future research are indicated.

Some ignition data were obtained with amyl nitrate, propylene oxide, and JP-4 fuel. The work was done at the NACA Lewis laboratory during May 1954.

APPARATUS AND PROCEDURE

The apparatus is shown in figure 1. Basic equipment design and instrumentation resulted from the selection of the method of thrust measurement. Exit thrust was measured as the difference between entering stream thrust and drag resulting from internal friction and momentum losses.

The combustion air entered through an electrical resistance heater which was thermostatically controlled by the inlet plenum air temperature. The inlet plenum temperature and pressure were recorded and designated as stagnation characteristics of the air flow at the burner inlet. A bellmouth nozzle adapted flow from the plenum to the $1\frac{7}{8}$-inch-diameter burner.

A labyrinth seal with pressure balancing provided leak-free flow from the plenum chamber to the burner inlet, and allowed free movement of the burner over a short axial distance.

The over-all burner length (28-in. length for the 15-in. combustion chamber or $20\frac{1}{2}$ in. for the $7\frac{1}{2}$-in. combustion chamber) was suspended

3482
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horizontally by springs in order to minimize sliding friction at the two plenum openings. The burner inlet static pressure, fuel, and ignition lines were connected in a manner to maintain flexibility. A flange section at the upstream end of the combustion chamber allowed convenient, rapid interchange of flame holders, injectors, and combustion chambers.

Near the center of the burner a double-arm, rigid beam provided contact through needle-bearings to the lever of a null-balance drag measuring device.

3482

The exit of the burner entered a plenum chamber equipped with numerous spray nozzles; the plenum vented to the atmosphere.

Spontaneous ignition and impulse data were collected simultaneously. Air flows and inlet-air stagnation temperatures were set. Then fuel was injected at a predetermined rate of flow for a period of several seconds. If spontaneous ignition occurred, a time interval of 6 to 10 seconds was allowed for collection of impulse data. If spontaneous ignition was not achieved, spark ignition was often used to start burning, in order to obtain impulse data.

After each run JP-4 fuel was flushed through the fuel lines in order to clear the pentaborane from the injector, thus preventing injector blockage by thermal degradation of the pentaborane.

The final configuration embodied one-point downstream, air-atomizing fuel injection. Any flame holders that might be used were situated immediately downstream of the injector. Maximum blocked area for both reported configurations (50 percent for bluff body and 35 percent for venturi types) occurred approximately 2.5 inches downstream of the injection point. In the extreme case a nonblocked burner was used consisting of the air atomizing injector, located as previously described in an open $1\frac{7}{8}$-inch-diameter burner.

Flame holders of other geometry and scale were tested. However, they were made of thin sheet metal and were rendered useless within a period of 2 to 3 seconds after burning was initiated and before steady-state operation could be obtained.

Spontaneous ignition data were taken with the following configurations:

(1) 15-inch combustor with 50 percent bluff body flame holders

(2) $7\frac{1}{2}$-inch combustor with no flame holder

Impulse data for combustion efficiency and pressure loss calculations were taken with the following configurations:

(1) 15-inch combustor with bluff body flame holder of 50 percent blocked area

(2) 15-inch combustor with venturi flame holder of 35 percent blocked area

(3) 15-inch combustor with no flame holder

(4) $7\frac{1}{2}$-inch combustor with venturi flame holder of 35 percent blocked area

(5) $7\frac{1}{2}$-inch combustor with no flame holder

3482

CALCULATION OF DATA

Calculations were based on principles of stream thrust conservation, mass continuity, and ideal gas relations. A gross drag measurement was utilized in the over-all force balance, and an exit area coefficient was calculated from nonburning conditions to be used as a correction for points with burning.

Symbols

The following symbols are used in this report:

A_b	burner cross-sectional area, sq ft
C_A	exit area coefficient, ratio of calculated effective exit area to burner area, A_e/A_b
D	net drag acting on stream tube, lb
F	stream thrust, lb
F^*	stream thrust at $M = 1$, lb
g	gravitational constant, 32.2 ft/sec^2
M	Mach number
m	rate of mass flow, slugs/sec
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft

Q dynamic pressure, lb/sq ft

R gas constant, 1543 ft-lb/($^{\circ}$R)(lb mol), 53.3 ft-lb/($^{\circ}$R)(lb air)

S_a air specific impulse at $M = 1$, lb thrust/(lb air)(sec)

t static temperature, $^{\circ}$R

V velocity, ft/sec

W_a rate of flow of air, lb/sec

γ ratio of specific heats

η efficiency

ρ density, lb/cu ft

φ equivalence ratio

Subscripts:

1 burner inlet

2 burner outlet

p exit plenum

i ideal

3482

Calculation Methods

Using the force balance, mass continuity equation, and an exit area coefficient determined under nonburning conditions results in the following force equation:

$$p_1 A_b + \frac{\rho_1 A_b V_1^2}{g} = p_2 C_A A_b + \frac{\rho_1 V_1 A_b V_2}{g} + D + p_p A_b \, (1 - C_A)$$

For the nonchoked case $p_2 = p_p$, and the exit velocity becomes

$$V_2 = V_1 + \frac{g}{\rho_1 V_1}\left(p_1 - p_2 - \frac{D}{A_b}\right)$$

The exit temperature was calculated using the mass continuity and ideal gas relation

$$t_2 = \frac{p_2 C_A V_2}{R_2 \rho_1 V_1}$$

where t_2 and R_2 were determined simultaneously.

The values R_2, γ_2, t_2, and S_a have been determined for products of complete combustion of pentaborane and air at various equivalence ratios φ_i and inlet air temperatures. The values of t_2 and S_a are given in references 8 and 9. Limitations are imposed on the data by assumption of combustion at 2 atmospheres with subsequent expansion to sonic velocity under conditions of "frozen" equilibrium.

3482

Recently published thermodynamic data for combustion of pentaborane-air mixtures (ref. 10) provide values for R_2, γ_2, and t_2 evaluated in terms of combustion pressure, inlet-air enthalpy, and equivalence ratio. These data do not require the assumption of "frozen" equilibrium expansion and a combustor pressure of 2 atmospheres, both of which are inherent in the data of references 8 and 9. Some burner exit temperatures t_2 calculated with these data ranged from 1 to 1.5 percent higher than t_2 yielded by the data of references 8 and 9. These calculated temperature increases occurred at conditions where differences in values of γ_2 and R_2 were at maxima within the available data. The changes in γ_2 and R_2 resulted from selection of values at 1 atmosphere rather than 2 atmospheres for $\Phi = 0.5$. This was the highest equivalence ratio extant for the new thermodynamic data. Accordingly, the thermodynamic data of references 8 and 9, which assumed frozen equilibrium and expansion from 2 atmospheres, were considered a suitable approximation for the computations presented herein.

Using

$$M_2 = \frac{V_2}{\sqrt{\gamma_2 g R_2 t_2}}$$

and γ_2, the value of F/F^* was selected from the gas tables (ref. 11). The value S_a was then calculated

$$S_a = \left(\frac{p_1 A_b + mV_1 - D}{W_a}\right)\left(\frac{F^*}{F}\right) = \frac{F_2^*}{W_a}$$

Using the calculated S_a and the relation for $S_{a,i}$ and φ_i for pentaborane combustion (ref. 8) gave φ_i. Combustion efficiency was taken as the ratio of ideal to actual equivalence ratio

$$\eta_c = \frac{\varphi_i}{\varphi}$$

Calculations for a choked burner exit differed in that $M_2 = 1$ was known rather than $p_2 = p_p$, which was known for the unchoked case; then for the choked condition

$$p_2 = \frac{p_1(1 + \gamma_1 M_1^2) - \frac{D}{A_b} - p_p(1 - C_A)}{C_A(1 + \gamma_2 M_2^2)} = \frac{p_1(1 + \gamma_1 M_1^2) - \frac{D}{A_b} - p_p(1 - C_A)}{C_A(1 + \gamma_2)}$$

Using $V_2 = \sqrt{\gamma_2 R_2 g t_2}$, $t_2 = p_2/R_2\rho_2$, and $\rho_1 V_1 = C_A \rho_2 V_2$ yields

$$t_2 = \frac{g\gamma_2}{R_2}\left(\frac{p_2 C_A}{\rho_1 V_1}\right)^2$$

The values t_2, R_2, and γ_2 were determined simultaneously using the previously described relations for pentaborane combustion at 2 atmospheres.

With $M_2 = 1$ and $F/F^* = 1$

$$S_a = \frac{F_2}{W_a}$$

and η_c was calculated as for the nonchoked case.

For determining pressure loss, P_1 was measured and P_2 was calculated:

$$P_2 = p_2\left(1 + \frac{\gamma_2 - 1}{2} M_2^2\right)^{\gamma_2/(\gamma_2 - 1)}$$

then

$$\frac{\Delta P}{Q} = \frac{P_1 - P_2}{\frac{1}{2}\rho_1 V_1^2}$$

3482

Values of η_c have been plotted against φ, while $\Delta P/Q$ is shown as a function of ρ_1/ρ_2.

RESULTS AND DISCUSSION

Spontaneous Ignition

The temperature and velocity at the combustor outlet at which spontaneous ignition of pentaborane occurred in two burner configurations is shown in figure 2. The limited fuel supply made it necessary to take spontaneous ignition and impulse data for combustion efficiency at the same time. Accordingly, the ignition data were taken over a range of equivalence ratios, and each point on the figure is labeled with its corresponding equivalence ratio. The combustor pressure was approximately atmospheric. The tests were made with the 15-inch-length combustor with the 50 percent blocked area bluff body and with the $7\frac{1}{2}$-inch length combustor with no flame holder. In each case it is seen that for the range of the conditions investigated the threshold of spontaneous ignition is governed principally by temperature. Vertical lines at 362° and 474° F are shown at the approximate spontaneous ignition temperature of the 15- and $7\frac{1}{2}$-inch combustors, respectively. The wider range of equivalence ratio and velocity used with the shorter combustor helps to illustrate the temperature dependence of spontaneous ignition in a ram-jet combustor environment. The two data points (fig. 2) closest to the spontaneous ignition line of the shorter combustor have equivalence ratios of 0.342 and 0.169 and velocities of 630 and 835 feet per second for the "no burning" and the "spontaneous ignition" points, respectively. Here an increase in temperature from 472° to 478° F made spontaneous ignition possible in spite of an accompanying large increase in velocity and a large decrease in equivalence ratio. The difference in the spontaneous ignition temperature between the 15-inch combustor with 50-percent-blocked area bluff body and the $7\frac{1}{2}$-inch open combustor indicate the effect of configuration change.

Flame holding and mixing devices modify the condition for incipient ignition in two ways:

(1) The residence period of portions of the combustible mixture is increased when zones of recirculating flow are created.

(2) The rate of heat loss from the preignition reactions that initiate combustion is altered by changed flow patterns and changes in the surfaces that act as heat sinks.

In reference 12 the ignition lag (residence time for spontaneous ignition) of propane-oxygen-nitrogen homogeneous mixtures was measured

for a range of temperatures. The ignition lag varied inversely as the fuel concentration, and increased with decreasing temperature. In the temperature range of the reference data from 968° to 1377° F, the spontaneous ignition temperature dependence on residence time and fuel concentration is not of the simple Arrhenius type with a constant activation energy. The influence of residence time and fuel concentration decreased with decreasing temperature. An investigation of the ignition delay (residence time for ignition) relation with temperature of kerosene fuel sprayed into the chamber is reported in reference 13. Tests were made at equivalence ratios of 0.073 to 0.184 and temperatures of 1481° to 1760° F. Within this range the ignition temperature was independent of the fuel-air ratio but the residence time decreased with increasing temperature according to the Arrhenius relation. A baffle was installed immediately upstream of the fuel injector. The baffle served to promote mixing and increase the residence period in its wake in the fuel induction zone. In the range of residence time comparable to that experienced in the present investigation the spontaneous ignition temperature was decreased substantially by the use of the small swirl inducing baffle.

3482

The absence of velocity dependence of the ignition temperature in the ram-jet combustor of this investigation is in contrast with the reported data of references 12 and 13; however, this difference may be explained by the following considerations:

(a) Both of the reference investigations were done at temperatures considerably higher than this work, and an extrapolation of their data indicates that at low temperatures a large increase in ignition lag accompanies a small decrease in temperature.

(b) In the reference investigations the combustion-chamber wall temperature was held close to that of the entering gas so that heat loss from the preignition reactions that initiate combustion is minimized. The combustor surfaces of this investigation were cooled by room temperature air.

For a nonadiabatic system such as this it is possible at some temperature for the rate of heat loss to the cold walls to become equal to the rate of heat generation from slow preignition reactions. For this condition an increase in residence time will not result in any increase in the net energy contained in the reacting gases; hence, spontaneous ignition will not result from an increase in residence time alone.

Amyl nitrate, propylene oxide, and JP-4 fuel were also tested (fig. 3) in the 50 percent bluff body combustor. Propylene oxide and JP-4 fuel would not ignite at an air temperature of 800° F and velocities of 340 and 310 feet per second, respectively. Efforts were made to spark ignite JP-4 and propylene oxide at these conditions to get impulse data.

However, ignition by spark was also impossible. The spontaneous ignition temperature of pentaborane in this combustor, 382° F, has been transcribed from figure 2. The data on amyl nitrate indicate that its ignition temperature in this combustor is approximately 690° F. Reference 13 reports the ignition temperature of amyl nitrate to be 780° F at a lag period of 30 milliseconds; kerosene had an ignition temperature of 1454° F in the same apparatus for the same lag period.

Combustion Efficiency

Figure 4 gives a comparison of the combustion efficiency of each of the burner configurations for a range of equivalence ratios. The combustion efficiency consistently increased with increase in burner length and blocked area of the flame holders. Equally consistent was the decrease in combustion efficiency with increasing equivalence ratio for the range covered with each of the configurations. Reference 10 reports combustion efficiencies of pentaborane in a full-scale ram-jet combustor of over 85 percent. Although combustion efficiencies were less sensitive to equivalence ratio variations than experienced in the $1\frac{7}{8}$-inch combustor, the trend of decreasing efficiency with increasing equivalence ratio was the same. This full-scale investigation was done with lower velocities and a longer combustor, so that the mixture residence periods varied from 3 to 12 times those in the work reported here.

The decrease in combustion efficiency with increase in fuel-air ratio may possibly be the result of rich oxidation of the pentaborane. Because of the wide flammability limits of pentaborane, burning can occur in regions that contain far too low an oxygen concentration to permit complete burning. Under these conditions products will form from decomposition and partial oxidation of the B_5; reference 14 indicates that some of these decomposition materials are far less reactive than pentaborane. These less reactive materials might then fail to burn completely in passing through the oxygen-rich regions of the combustor. With an increase in the over-all fuel-air ratio the tendency toward this rich oxidation should be increased. The foregoing hypothesis would also account for the improved combustion efficiency obtained with increased blocked area of the flame holder; an increase in flame holder blockage gives improved fuel-air mixing and this will reduce the opportunity for the fuel-rich oxidation to occur.

Hydrocarbon fuels decompose in a similar manner when subjected to oxidation in a fuel-rich environment. However, in the case of hydrocarbons the concentration of relatively unreactive products (soot) is generally quite low, and most of the degradation products are more reactive than the parent material. The limited experience with boron hydrides has not yet completely defined the influence of mixture ratio

on flammability or provided comprehensive flame-speed data. Reference 6 reports that homogeneous, quiescent diborane-air mixtures at atmospheric pressure were ignited at equivalence ratios below 0.3 and had spatial flame speeds at least as high as 170 feet per second. By extrapolating the data of pentaborane-hydrocarbon mixtures in references 3 and 7 it is evident that pentaborane alone must have a much higher flame speed and much wider flammability limits than hydrocarbons.

The design principle required for combustors using a highly reactive fuel such as pentaborane are therefore quite different than those required for conventional combustors. With pentaborane, the primary consideration is to obtain rapid mixing of the fuel and air. With hydrocarbons, the primary considerations are to provide a highly wrinkled flame front (to compensate for the low fundamental flame speed of these fuels) and to obtain a large amount of recirculatory flow in the combustor (to insure the existence of vapor fuel-air mixtures within the narrow flammable range for these fuels). In the operation of various combustors with pentaborane alone at the NACA Lewis laboratory flame blow-out has never been experienced; it is probable that the limits of stream velocity have not been reached and that such limits will be governed by the ability of fuel-air mixing devices to create optimum mixture ratios in very small time periods.

3482

Friction Pressure Loss

An indication of the relative total-pressure losses for each of the burner configurations of figure 4 is shown in figure 5. The friction pressure losses correlate with the efficiency levels of each of the combustors. The combustors with high efficiency had high pressure loss.

The group of data points for each configuration that cluster around the minimum density ratio for each case are those for the condition of no burning and no fuel flow. Cold-flow data were taken between each of the points where fuel was burned.

In all the configurations except the 15-inch combustor with 50 percent bluff body the isothermal pressure drop was altered very little by consecutive burning periods. However, with this combustor the deposits of oxide and fuel decomposition products on the upstream flame holder surfaces during each of the burning periods made progressive increases in the cold-flow friction loss. The data points are numbered to show their order. Numbers 7 and 8 are both for cold flow; the increase in friction drop is due to fuel being burned between the two for too short a period for the data recorders to operate properly.

The solid circles are data corrected as follows: Each of the hot-flow data points was corrected for oxide deposition by diminishing its value by the difference between the friction loss ($\Delta P/Q$) of its corresponding (subsequent) cold point and the friction loss of the clean combustor, point number 1. A solid line showing the theoretical increase in $\Delta P/Q$ due to heat addition after an initial cold-flow friction loss has been drawn through the cold-flow value for $\Delta P/Q$ taken with a clean combustor in the 15-inch combustor with 50 percent bluff body flame holder. The corrected points approach the theoretical line. The solid deposits apparently affect the cold-flow friction and have little influence on flow in the combustion zone. Also, the deposits are quite thin on the combustor walls, but block a considerable area in the zone of the fuel injector and flame holder.

3482

Fuel Injection

It was felt that efficient fuel spreading might be accomplished by eight-point upstream injection at the section of maximum blocked area in the venturi configuration. However, this proved unsatisfactory because any slight malfunction at the injector orifices caused wall impingement of the fuel; this, in turn, resulted in combustion chamber failure within a few seconds of burning. It was concluded that the small combustor diameter obviated such an approach.

When the flow of pentaborane was interrupted at the end of a combustion test, the small amount of the injection tube in the combustor was heated up before the walls and inlet air supply could be cooled. The result was an accumulation of decomposition products that clogged the injector and could not easily be removed. The problem was solved by flushing the injector with JP-4 fuel immediately after the pentaborane flow was shut off.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 8, 1954

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3462

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3482

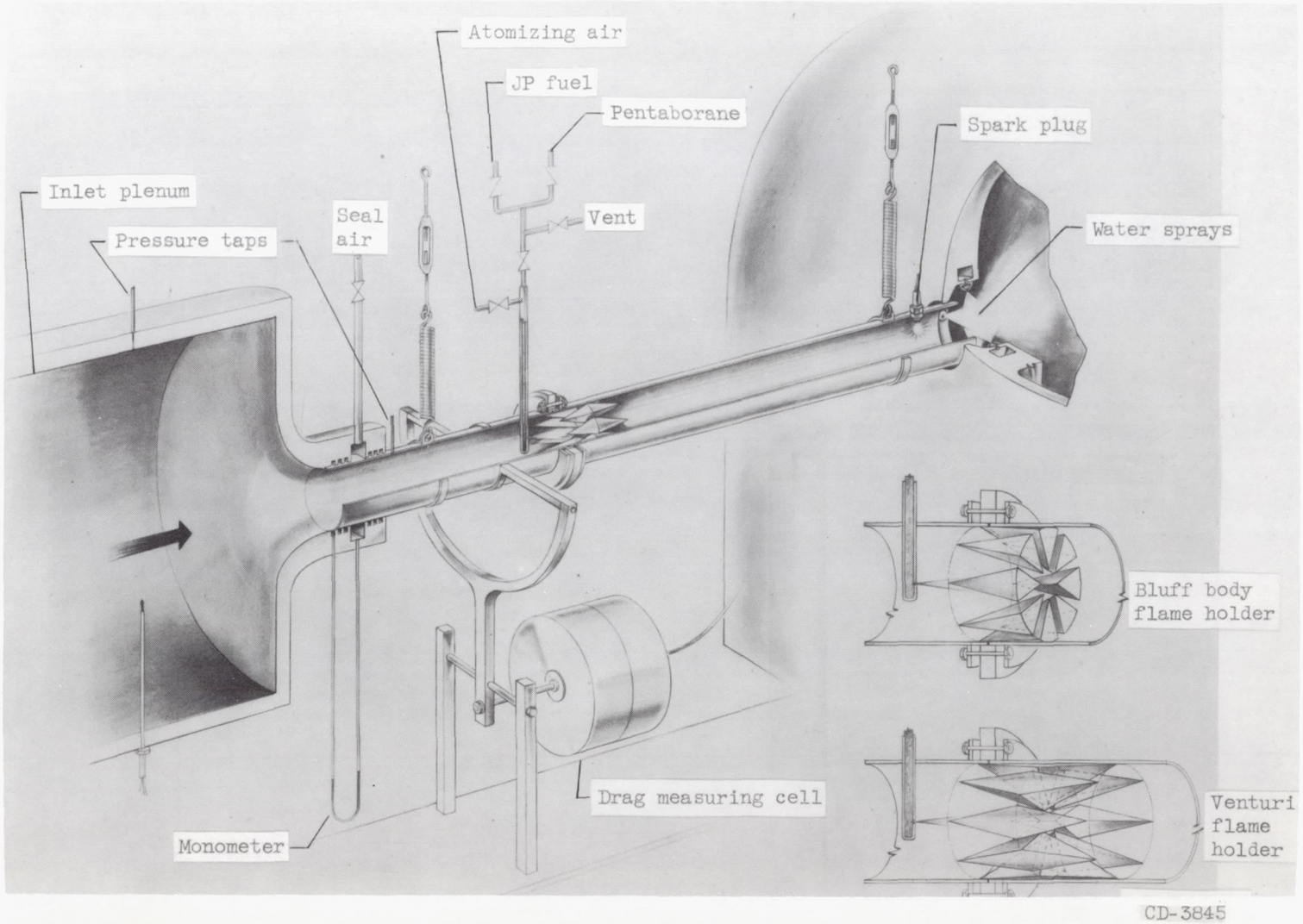

Figure 1. - Test setup.

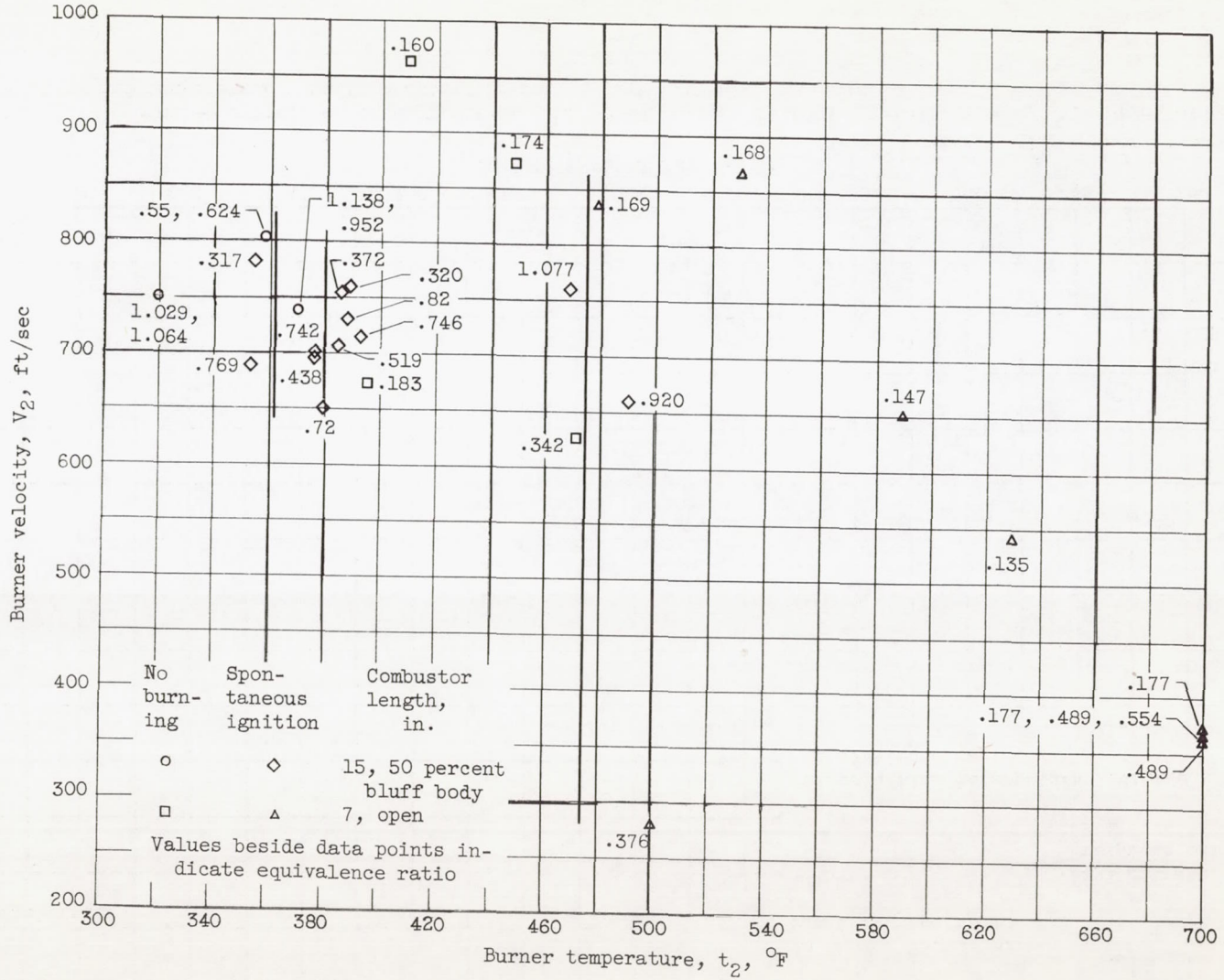

Figure 2. - Spontaneous ignition of pentaborane as a function of outlet velocity and temperature for two combustor configurations.

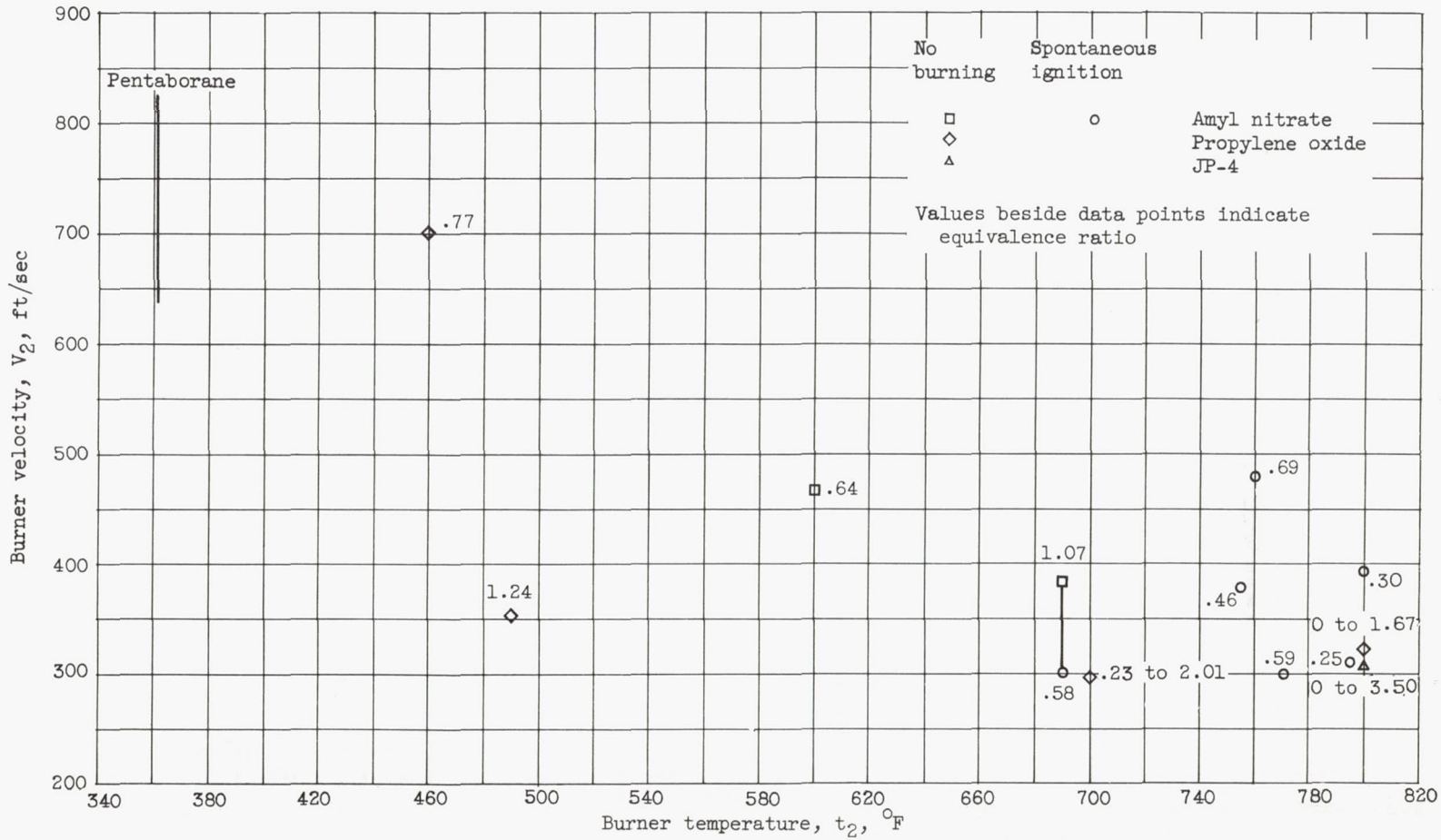

Figure 3. - Spontaneous ignition of amyl nitrate, propylene oxide, JP-4, and pentaborane as a function of outlet velocity and temperature. Configuration, 15-inch length with 50-percent bluff body.

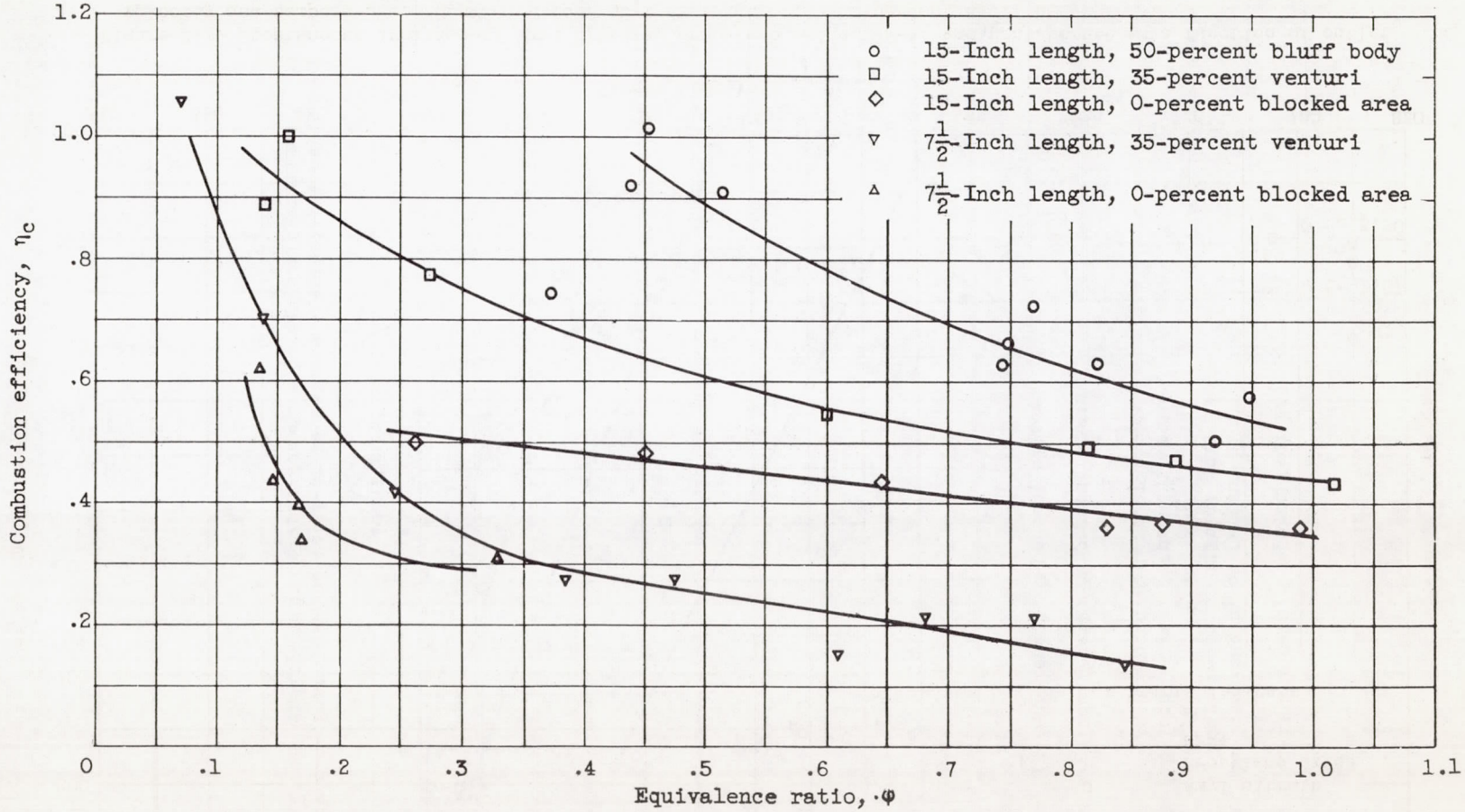

Figure 4. - Pentaborane combustion efficiency for five burner configurations.

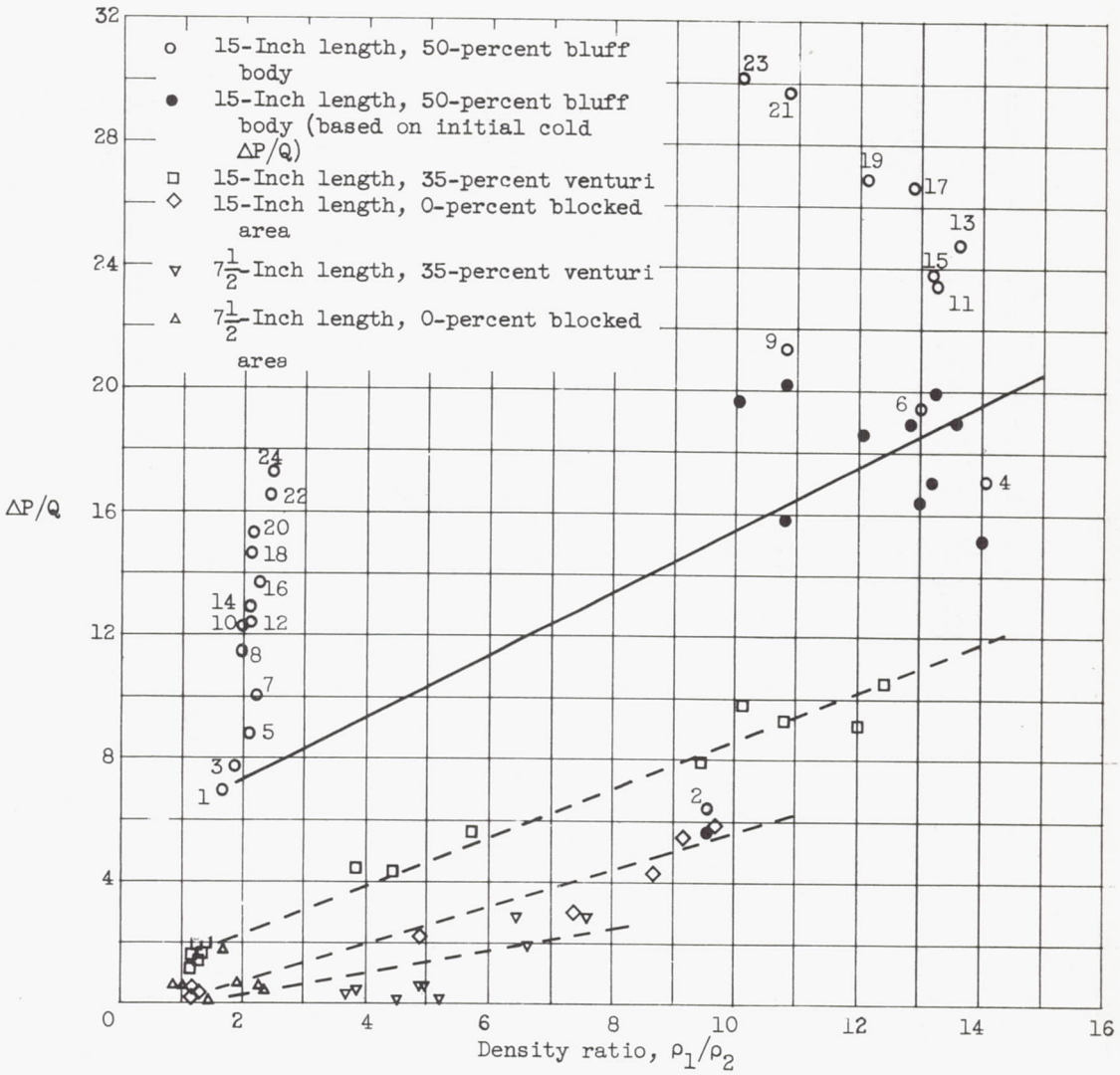

Figure 5. - Dependence of total-pressure loss - entering kinetic head ratio $\Delta P/Q$ on density ratio ρ_1/ρ_2 for five burner configurations.

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